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INFLUENCE OF CRYSTAL STRUCTURE ON FRICTION CHARACTERISTICS OF RARE-EARTH AND RELATED METALS IN VACUUM TO 10^{-10} MILLIMETER OF MERCURY

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SUMMARY

The friction, wear, and metal-transfer characteristics were determined for rare-earth and related metals in vacuum to 10^{-10} millimeter of mercury. The metals studied were lanthanum, neodymium, praseodymium, cerium, holmium, erbium, gadolinium, dysprosium, samarium, yttrium, and thallium. Friction and wear experiments were conducted with the rare-earth or related metals generally sliding against 440-C stainless steel at sliding velocities to 2000 feet per minute and loads to 3000 grams. The rare-earth or related metals were the rider specimens (3/16-in.-rad. hemisphere) sliding on flat $2\frac{1}{2}$-inch-diameter disk specimens of 440-C stainless steel. Factors studied were the effects of crystal structure and crystalline phase changes on the friction, wear, and metal-transfer characteristics of these metals in vacuum.

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The results of the investigation indicate that crystal structure markedly influences friction, wear, and metal-transfer characteristics of the rare-earth and related metals in vacuum. Close-packed hexagonal crystal forms of the rare earths and of thallium had much lower friction, wear, and metal-transfer characteristics than face-centered or body-centered cubic structures. The lowest friction coefficients were obtained with those rare-earth metals that have the largest c-axis (crystal height), that is, those metals with the lanthanum- and samarium-type crystal structures. With neodymium a crystal transformation was observed at a temperature below that reported in the literature.

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INTRODUCTION

Lubrication of mechanical components for space devices requires the selection of lubricants and other materials having extreme stability in a space environment. The rare-earth metals, atomic numbers 57 to 71 (lanthanum, . . . ,

end of the retaining arm from the rider specimen was connected to a strain-gage assembly, which was used to measure frictional force. Load was applied through a deadweight loading system. In order to heat the specimens, a small tantalum-wire-wound heater was placed around the disk and the rider specimens, and the specimens were radiantly heated. The bulk rider specimen temperatures were measured with a thermocouple positioned in the body of the rider.

Attached to the lower end of the specimen chamber was a 400-liter-per-second ionization pump and a mechanical forepump with liquid-nitrogen and zeolite traps. The pressure in the chamber was measured adjacent to the specimen with an inverted magnetron cold-cathode gage (Kreisman). In the same plane as the specimens and the ionization gage was a diatron-type mass spectrometer (not shown in fig. 1) for determination of gases present in the vacuum system. A coil of 5/16-inch-diameter stainless-steel tubing 20 feet long was used for either liquid-nitrogen or liquid-helium cryopumping of the vacuum system.

SPECIMEN FINISH AND CLEANING PROCEDURE

The disk and the rider specimens used in friction and wear experiments were finished to a roughness of 4 to 8 microinches. Before each experiment, the disk and the rider were given the same preparatory treatment: (1) thorough rinsing with acetone to remove oil and grease, (2) polishing with moist levigated alumina on a soft polishing cloth, and (3) thorough rinsing with tap water followed by distilled water. For each experiment, a new set of specimens was used.

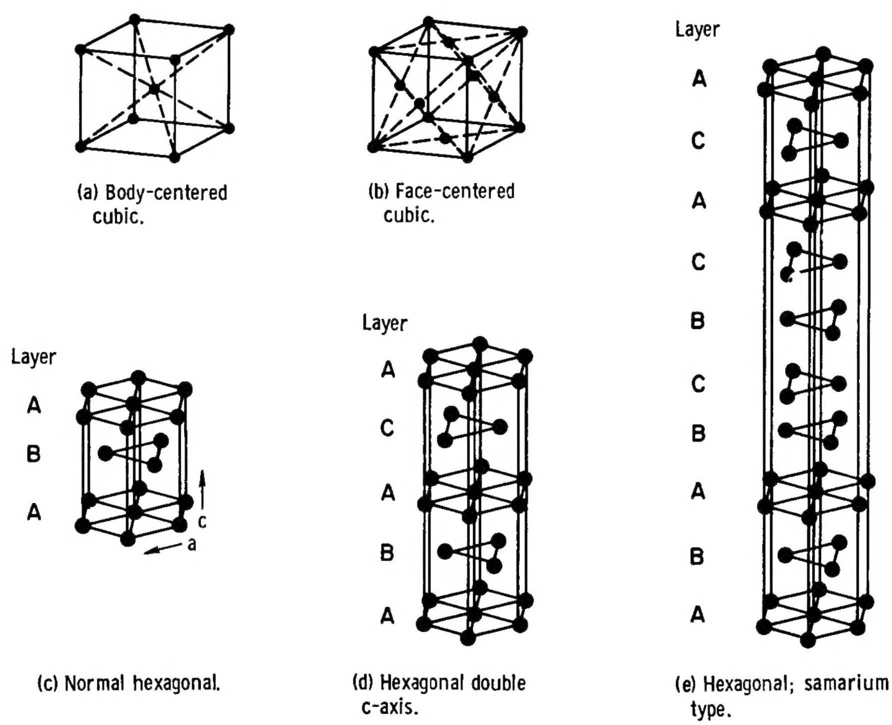


Figure 2. - Crystal structures.

RESULTS AND DISCUSSION

Polymorphism in Rare-Earth Metals

An interesting property of the rare-earth metals is their crystal structure. Many of these metals have a close-packed hexagonal crystal structure at room temperature. The hexagonal forms in which the rare earths may exist are of three types. These types are compared with body-centered and face-centered cubic structures in figure 2. The first or normal hexagonal form (fig. 2(c)) with the ABA stacking sequence of the A and the B layers is that represented by metals such as magnesium and in the rare-earth series by such metals as holmium, erbium, and gadolinium. This particular form of hexagonal structure has the shortest c-axis (crystal height) lattice constant. The second type of hexagonal crystalline form is the hexagonal double c-axis or the lanthanum-type crystal structure (fig. 2(d)) with ABACA stacking sequence of the A, B, and C layers. This crystalline form characterizes lanthanum, neodymium, and praseodymium. The third form is the samarium type (fig. 2(e)) with the stacking sequence ABABCBCACA. The c-axis lattice constant of this particular form is four and a half times that of the normal hexagonal structure. Some research investigators have termed this structure "rhombohedral" (refs. 8 and 9).

Many of the rare-earth metals undergo crystal transformation. Lanthanum, for example, will transform from a hexagonal crystal structure to a face-centered cubic structure at about 500° F as shown in figure 3 and transform from the face-centered cubic to a body-centered cubic structure at 1594° F. Transformations from hexagonal to body-centered cubic structure occur with neodymium at 1584° F and with praseodymium at 1472° F. Cerium, as indicated in figure 3, undergoes three crystal transformations. Cerium transforms from the

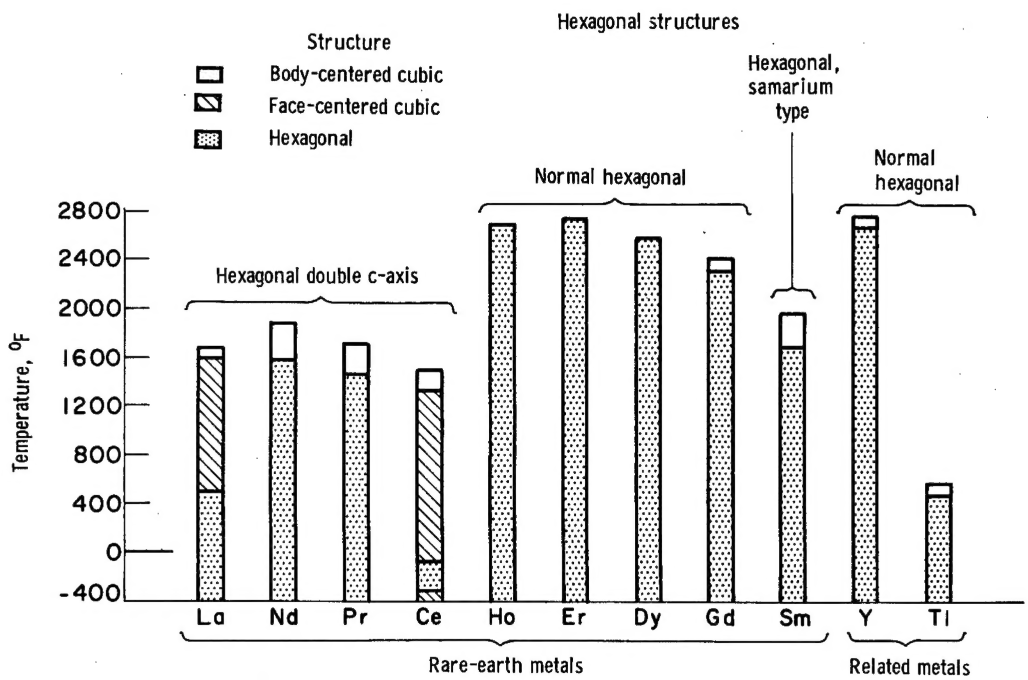
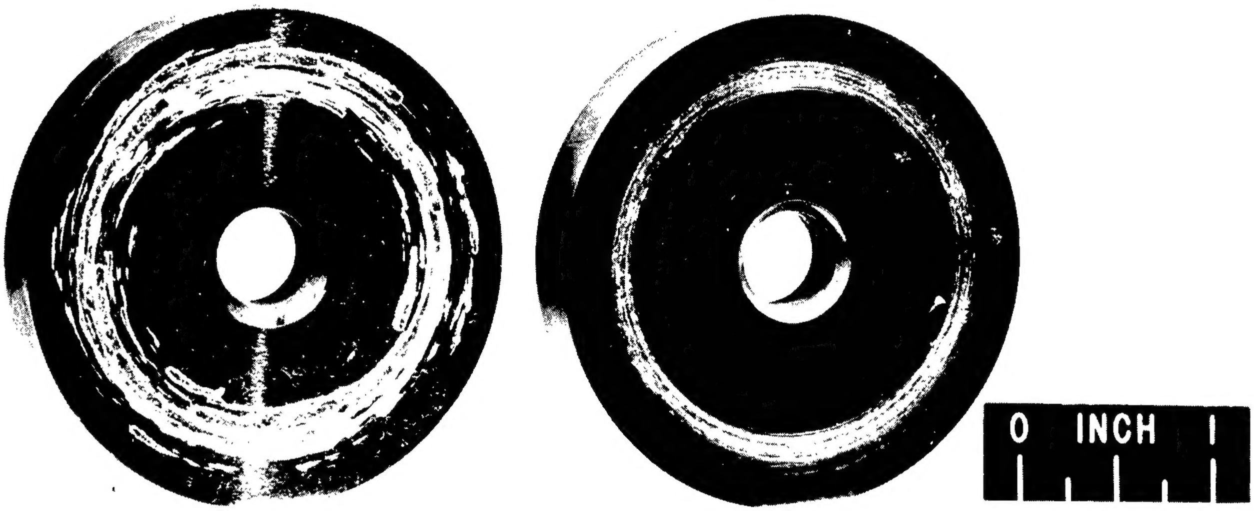


Figure 3. - Crystal transformations indicated in the literature for rare-earth and related metals (ref. 1).



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(a) Sliding velocity, 980 feet per minute. (b) Sliding velocity, 196 feet per minute.

Figure 5. - 440-C stainless steel disk specimens. Rider specimen, lanthanum; load, 1000 grams; ambient pressure, 10^{-9} millimeter of mercury; ambient temperature, 75°F; duration of run, 1 hour.

TABLE III. - WEAR FOR VARIOUS RIDER MATERIALS

[Sliding against hardened 440-C stainless steel; load, 1000 g; ambient pressure, 10^{-9} mm Hg; duration of experiment, 1 hr.]

Material	Hardness (DPH)[a]	Sliding velocity, ft/min	Rider wear, cu in./ft sliding
Lanthanum	40	200 980	3.40×10^{-9} 14.18
Samarium	45	390	1.31×10^{-9}
440-C stainless steel	600	390	10.47×10^{-9}

[a]Diamond pyramid hardness.

specimen against the disk. This behavior pattern is analogous to that observed with other cubic structures (e.g., iron and nickel) in vacuum. The result of this behavior can be seen in the photographs of the 440-C disk specimen of figure 5. At a sliding velocity of 980 feet per minute (cubic structure), mass metal transfer of lanthanum to the 440-C disk specimen occurred. The globules of metal transferred in some instances stood 3/32 inch above the 440-C surface. With the same material combination at 196 feet per minute (hexagonal structure), the run was very smooth and a very thin transfer film of lanthanum to 440-C was observed. The wear values to lanthanum obtained at the two sliding velocities are presented in figure 4(b) (p. 6) and in table III.

Reference 1 indicates that the crystal transformation of lanthanum is pressure sensitive. Increasing the load upon the lanthanum rider specimen should induce the crystal transformation. Examination of the friction coefficient as a function of load in figure 4 indicates that increasing the load can bring about the crystal transformation. This transformation, however, could be due to increasing temperature resulting from increasing load. At loads above 1500 grams the coefficient of friction begins to increase. If

after running at 2500 grams the load is reduced to 1000 grams the friction coefficient remains high. The specimens were allowed to stand overnight unloaded. At 500 grams the friction returned to near the original value, which indicated again the reversibility of the crystal transformation of lanthanum.

Although in those experiments with the lanthanum sliding on 440-C a transfer film of lanthanum to 440-C resulted in lanthanum sliding on lanthanum, it was decided to determine the friction characteristics of lanthanum sliding on itself. The friction results obtained at various sliding velocities with lanthanum sliding on lanthanum are presented in figure 6. At sliding velocities below 350 feet per minute the friction coefficient was less than 0.4. When the sliding velocity was increased above 375 feet per minute, the friction coefficient increased and reached a value of about 1.4. The increase occurred at approximately the same sliding velocity encountered with lanthanum sliding on 440-C stainless steel. When the specimens were allowed to cool, the friction coefficient returned to the original value (less than 0.4), which again attested to the reversibility of the crystal transformation.

Although the concept of the influence of solid solubility on friction, wear, and welding tendencies is frequently referred to in this literature, the data obtained with lanthanum sliding on lanthanum would seem to indicate that crystal structure may be of appreciable importance.

Neodymium

Neodymium, praseodymium, and lanthanum have, among the rare-earth metals, the greatest similarities in both chemical and physical properties. The literature (refs. 1 and 2), however, does not indicate a crystalline transformation for neodymium from the hexagonal form below 1584° F. Friction experiments were therefore conducted as a function of sliding velocity and temperature for neodymium (99 percent, with praseodymium as the principal impurity) sliding on 440-C stainless steel. The results obtained in these experiments are presented in figure 7. Based on the high temperature associated with the transformation from the hexagonal to the body-centered form, the friction coefficient was anticipated to remain relatively low in the range of sliding veloc-

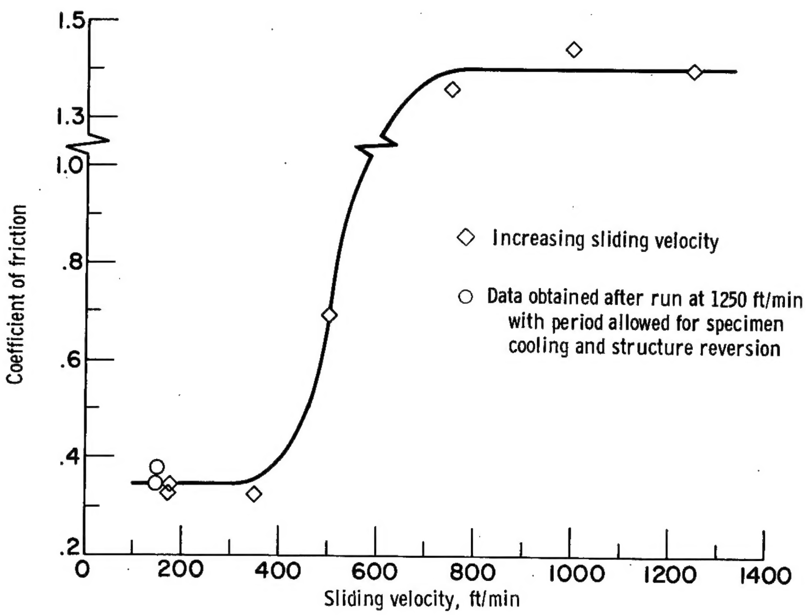

Figure 6. - Coefficient of friction for lanthanum sliding on lanthanum at various sliding velocities in vacuum (10^{-9} mm Hg). Load, 500 grams; ambient temperature, 75° F.

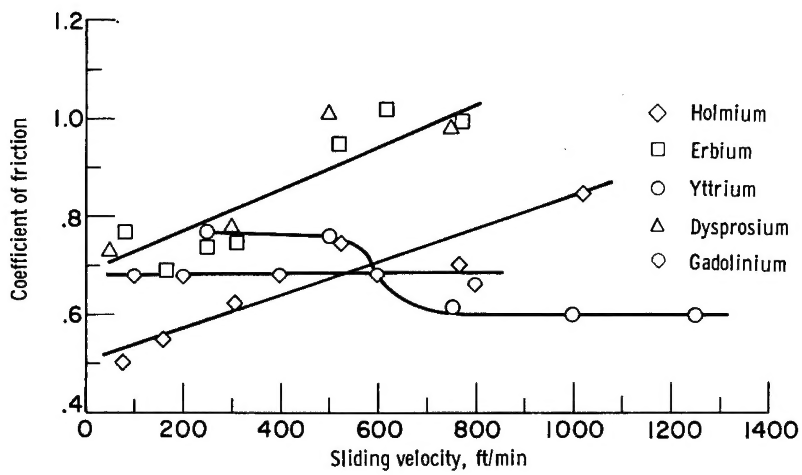

Figure 9. - Coefficient of friction of various rare-earth metals sliding on 440-C stainless steel in vacuum (10^{-9} mm Hg). Load, 1000 grams; ambient temperature, 75^0 F.

friction with the magnesium-type structure of erbium, holmium, gadolinium, dysprosium, and yttrium are higher than those obtained with those metals possessing the lanthanum-type hexagonal form.

Samarium

The most complex hexagonal crystal form is that of the metal samarium (refs. 9 and 10; see fig. 2, p. 4). The friction coefficients for samarium sliding on 440-C at various sliding velocities in vacuum were determined and the results obtained are presented in figure 10. The coefficient of friction for samarium showed a slight increase with increasing sliding velocity. The friction values were, however, lower than those obtained with the materials possessing the simple magnesium-type hexagonal crystal form. The mean values obtained with samarium sliding on 440-C were very much lower than those obtained with 440-C sliding on 440-C despite a wide margin of difference in hardness (see table III, p. 8).

Effect of Hexagonal Crystal Form on Friction

If the three hexagonal crystal forms of the rare-earth metals are considered, the lowest friction coefficients are obtained with the lanthanum- and samarium-type structures. The rare earths and yttrium with the simple hexagonal, magnesium-type structure exhibit higher friction coefficients. Examination of lattice constants for the crystalline forms indicate variations in the c-axis. The friction coefficients for the rare earths, plotted as a function

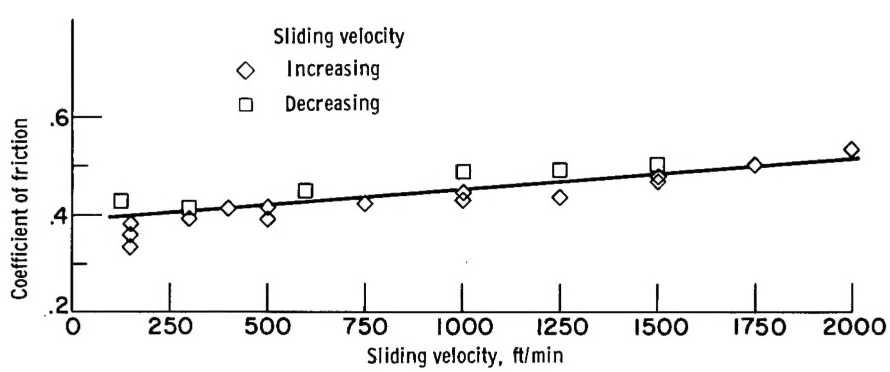

Figure 10. - Coefficient of friction of samarium sliding on 440-C stainless steel in vacuum (10^{-9} mm Hg). Load, 1000 grams; ambient temperature, 75^0 F.

of c-axis length in angstroms, are presented in figure 11. The metals with the smallest c-axes exhibit the highest coefficients of friction.

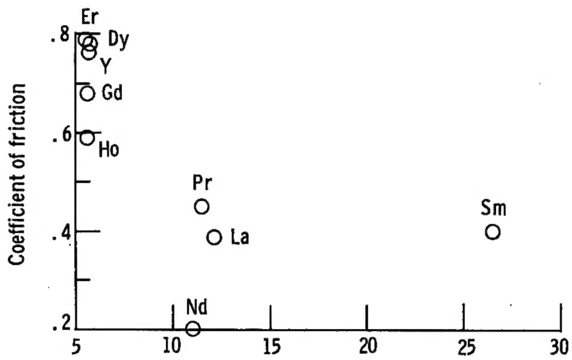

Figure 11. - Coefficient of friction as function of axis length in hexagonal crystal system of rare-earth metals. Ambient pressure, 10^{-9} millimeter of mercury; load, 1000 grams; sliding velocity, 250 feet per minute; ambient temperature, 75° F.

Thallium

In addition to the rare-earth metals there are other metals that exhibit polymorphism. Iron, cobalt, tin, zirconium, rhodium, hafnium, thorium, titanium, and thallium are some of these (ref. 11). Thallium metal has a close-packed hexagonal crystal form below 446° F. Above this temperature, it is transformed to the body-centered cubic structure. In order to determine the effect of crystal transformation on a metal outside the rare-earth series, some friction experiments were conducted with thallium metal sliding on 440-C in vacuum. Thallium metal was selected because it has a relatively low transformation temperature and has the normal hexagonal structure at room temperature. In addition it can be obtained with high purity. The material used in this study was 99.999 percent pure. The results obtained in the friction experiments are presented in figure 12.

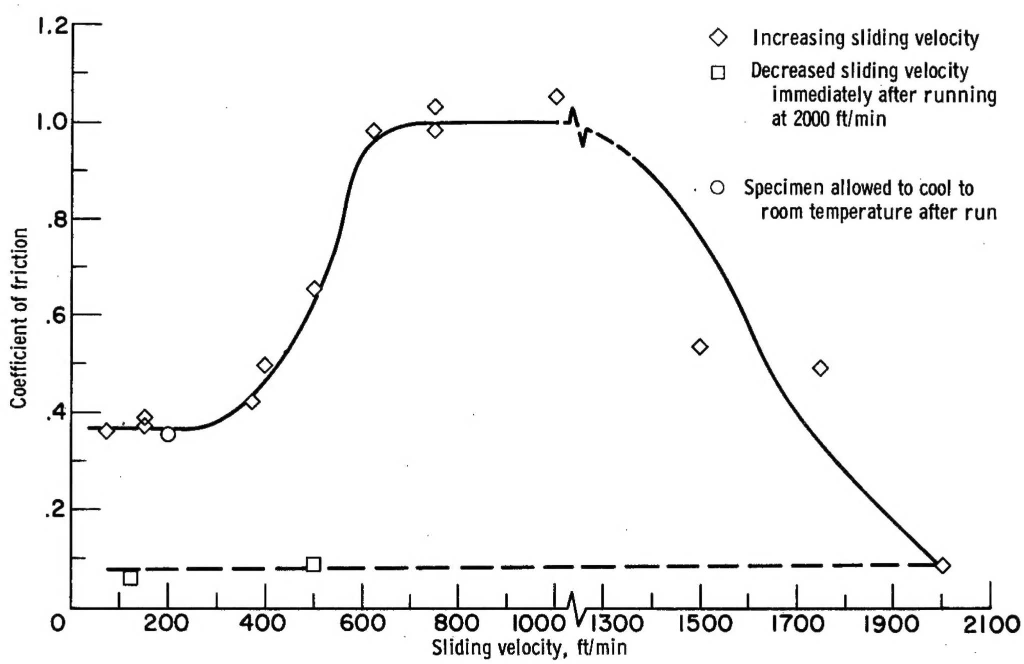

Figure 12. - Coefficient of friction for thallium sliding on 440-C stainless steel in vacuum (10^{-10} mm Hg). Load, 1000 grams; ambient temperature, 75° F.

At sliding velocities of less than 200 feet per minute the coefficient of friction was less than 0.4. The friction coefficient increased markedly at

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